tegration of related Hankel transforms by quadrature and continued fraction expansion (Chave, 1983) was chosen and proved to be very reliable. The sacrifice in computing efficiency for the ground EM over the AEM inversion method is more than offset as many fewer observations are measured on a typical ground survey.

The inversion technique is easily adaptable to new EM systems and coil configurations as they become available. It is hoped that the technique will be extended to the inversion of time-domain EM data. Joint inversion of ground EM and resistivity sounding data will be attempted. The methods for inversion of AEM and ground EM data to a layered earth model have brought an added dimension to frequency-domain EM interpretation. Not only is the geophysicist provided with values for layer depths, apparent resistivities, thickness, etc., but also a specific knowledge of the accuracy and contribution of each fitted parameter to the model. This serves to greatly reduce the ambiguities inherent in the EM method.

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Interpretation of Tipper Survey Data MIN 2.6

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For a number of geologic structures, information on the electrical and geometric properties of the section can be directly determined from tipper profiles acquired using natural or VLF radio transmitter sources. The interpretation process is simple and rapid. It is based on relations between the parameters of the observed profile data and the properties of the geologic model under consideration. These relations are presented in the form of a series of charts for dipping contacts and buried vertical contacts. The tipper phase is used to limit the effect of a fixed polarization of the horizontal primary field, as is the case in the VLF method. A field example is used to demonstrate that our procedure yields reasonable results.

Introduction

Measurements of the vertical magnetic field associated with plane, horizontally polarized magnetic field sources provide an efficient method for mapping subsurface lateral electrical conductivity discontinuities. Source fields, spanning a range of frequencies from 10^{-4} Hz to 60 kHz, can be used in a number of applications ranging from deep crustal investigation to engineering studies. In a horizontally layered geology, the ratio of the electric to magnetic fields completely describes the subsurface electrical conductivity structure. In the presence of lateral conductivity variations, however, the electrical current distribution is distorted and a vertical magnetic field is the direct consequence of changes in the concentration of current flowing parallel to the conductivity variation. Thus, the transverse electric (TE) mode is composed of the magnetic field perpendicular to strike, the electric field parallel to strike, and the vertical magnetic field. No closed form analytic solution exists for this mode and the computation of the response over a given geologic model and all interpretation techniques are based on approximations or numerical solutions. Field data therefore proved difficult to interpret and, in fact, the cost of interpretation can easily exceed the cost of data acquisition.

We devised a simple method of interpreting profiles for two common geologic features. Our graphic method of interpreting vertical field data is based on an empirical relationship between the parameters of the observed anomaly and those of the numerical solution of the assumed geologic model. It requires no prior knowledge of the subsurface resistivities. The two geologic features studied are the outcropping contact with a variable dip, and the vertical contact with an overburden layer. The procedure for interpreting the survey data can be performed in the field in a few minutes and requires measurements at only one frequency.

Contact interpretation

Telford et al. (1977) showed how peak tipper magnitude calculated for a profile over a covered vertical contact relates to the resistivities in the section and the thickness of the conductive overburden layer. The tipper magnitude alone cannot lead to a unique determination of the resistivity contrast and the overburden thickness. Extending the relationship to include the corresponding phase and anomaly shape reduces the ambiguity. Furthermore, in the case of an outcropping contact, the dip and resistivities can be resolved unambiguously. The anomaly parameters required for interpretation are indicated in Figure 1. They are the peak tipper magnitude $|T_p|$; its phase ϕ_p; the distances x_c and x_r, to the points on both the conductive and resistive sides where the tipper is reduced to half its peak value; and the tipper phase at these points, ϕ_c and ϕ_r.

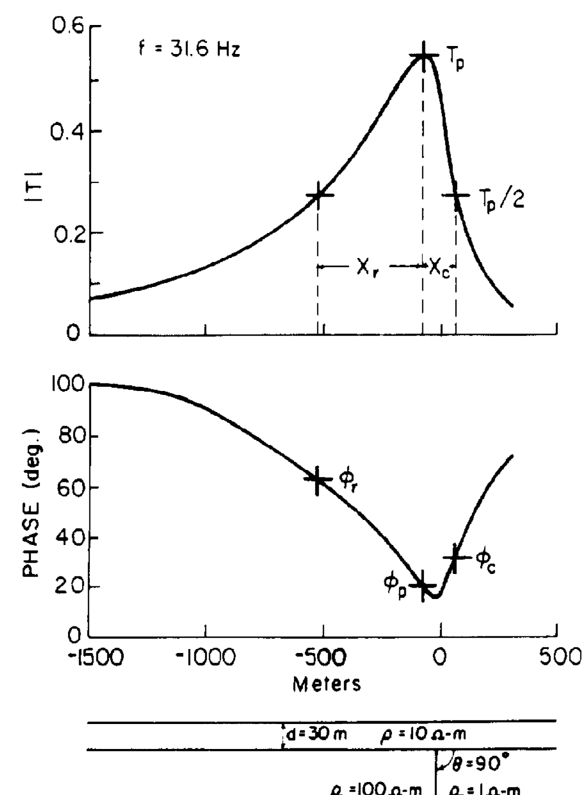

FIG. 1. Numerical solution of a vertical contact with a 100 Ω·m resistor and 1 Ω·m conductor under a 30 m thick, 10 Ω·m overburden at 31.6 Hz. Tipper amplitude and phase profiles show parameters required for interpretation.

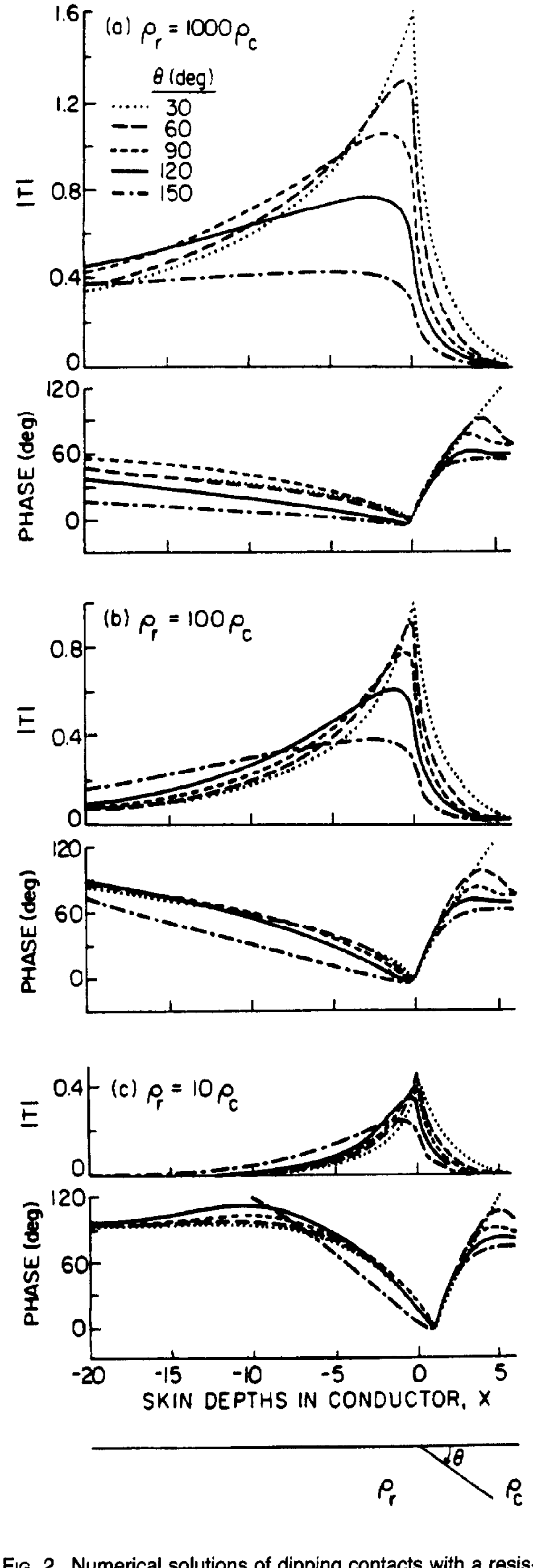

FIG. 2. Numerical solutions of dipping contacts with a resistivity ratio of top, 1 000:1; center, 100:1; and bottom, 10:1. Tipper magnitude and phase for dips of 30°, 60°, 90°, 120°, and 150°. Horizontal scale in units of skin depth in the conductor.

Contact with variable dip and no overburden. The simplest geologic case which can be resolved by tipper profiles is the contact with a variable dip and no overburden. Figure 2 shows theoretical values of the tipper magnitude and phase for contacts with a resistivity contrast of 1 000:1, 100:1, and 10:1, at several dips. The first step of the interpretation is performed by examination of the phase along the profile. The maximum anomaly gradient appears on the conductive side of the contact. The position of the contact is found to be very nearly coincident with the position of the minimum phase.

The validity of the dipping surficial contact model is determined from the phase of the peak tipper. Examination of the models shows that the peak tipper is entirely in-phase. Thus the charts in Figures 3 and 4 can be used to interpret profiles whose phase of the maximum tipper is less than 10 degrees. First, the resistivity contrast at the contact and its dip are determined from the chart in Figure 3 which relates these parameters to ϕ_r, the tipper phase at the resistive half-width point and F_s the ratio of the conductive to resistive half-widths x_c/x_r. The contrast and dip are then used in the chart in Figure 4 to determine γ_c, the number of skin depths that correspond to the anomaly half-width on the conductive side. The resistivities are computed from the relation:

$$\rho_c = \left[\frac{x_c\sqrt{f}}{503\gamma_c}\right]^2, \tag{1}$$

where ρ_c = resistivity in Ω-m on the conductive side, x_c = half-width in meters on the conductive side, γ_c = half-width in skin depths x_c/δ_c from Figure 4, $\delta_c = 503\sqrt{\rho_c/f}$, and f = frequency

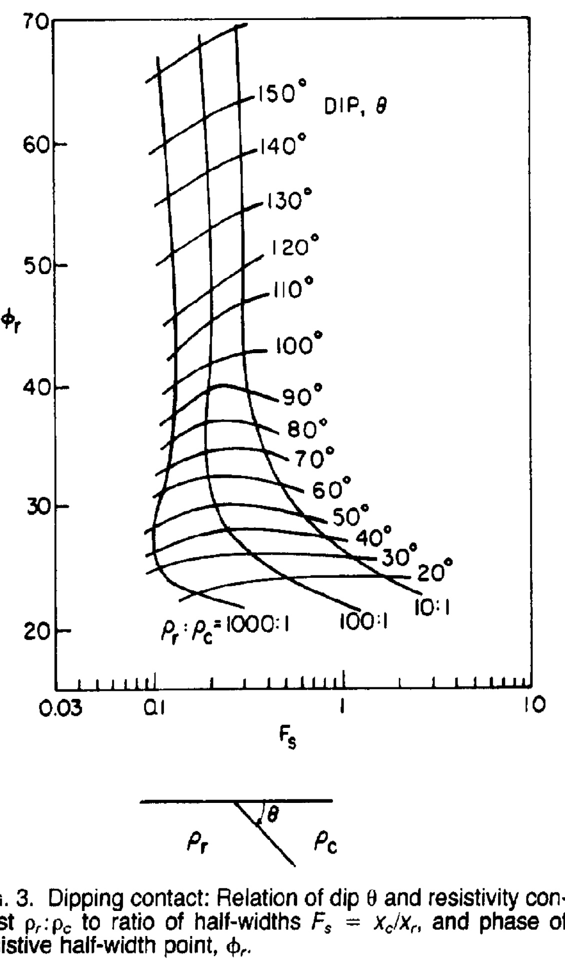

FIG. 3. Dipping contact: Relation of dip θ and resistivity contrast $\rho_r:\rho_c$ to ratio of half-widths $F_s = x_c/x_r$, and phase of resistive half-width point, ϕ_r.

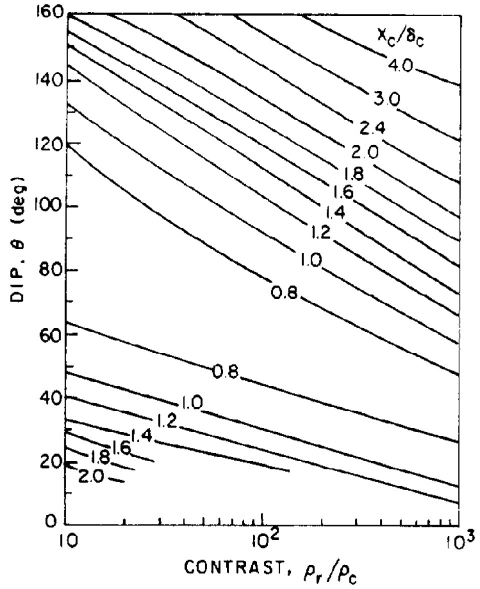

FIG. 4. Dipping contact: Relation of conductive half-width in units of skin depths in the conductor to dip and resistivity contrast.

in hertz at which the data were required. The resistivity of the resistor is determined from the contrast value obtained previously.

Contact with an overburden layer. A more complicated geologic case is the contact covered by an overburden layer. The overburden alters the response which now not only depends on the contact characteristics but also depends on the relation of the overburden resistivity to those of the underlying formations as well as the contact dip. In this case the tipper phase at the contact is no longer 0, but increases with increasing overburden thickness. Unambiguous determination of the 5 model characteristics (i.e., the three resistivities, the thickness of the overburden, and the dip) requires 5 parameters: peak tipper magnitude and phase; the ratio of the conductive to the resistive half-width; and the phases at the half-widths. Relating 5 parameters to 5 characteristics graphically is impossible. Nevertheless, it was found that if the dip is fixed, then a simple graphic interpretation of single-frequency tipper profiles is possible for a broad range of models. The procedure for interpreting vertical contacts covered by overburden is similar to that for the dipping contact discussed above. The identification of the resistive and conductive sides of the contact and its location are performed by visual examination of the profile data. A set of charts is then used to determine the resistivities of the contact and overburden, and the overburden thickness. Because our interpretation method relies solely on the phase relations and shape of the profile, it can be used to interpret fixed transmitter VLF data, regardless of the orientation of the transmitter to the contact. The only requirement is that the vertical field produced be measurable. This can be seen by examining the dependence of the field quantities on the transmitter azimuth. For scalar measurements, the amplitude of the vertical field, and to the first order the tipper, is a function of the cosine of the angle between the strike of the contact and the azimuth to the transmitter (Patterson and Ronka, 1971). The phase and shape of the profile are relatively unaffected by transmitter orientation.

Field example

The dipping surficial contact interpretation was applied to a profile over a metasedimentary sequence in north-central Washington state. Tensor magnetotelluric data, including vertical magnetic field, were collected over a frequency range of 1 to 500 Hz. Profile data were originally interpreted by trial-and-error matching of both tensor impedance and tipper to 2-D forward models. The best interpretation of this profile is a dipping bed, 100 m wide, striking northwest and dipping northeast at 20 degrees. The bed was determined to have a resistivity of 1 Ω·m and the host rock 1 000 Ω·m. The overburden appears to be quite thin, less than 5 m, with a resistivity of approximately 40 Ω·m. At 100 Hz, this overburden represents less than 0.02 skin depths and has a very small effect on the response. The northeastern contact has virtually no vertical field response, a characteristic of a shallow dip with the resistor over the conductor. This contact is only discernible from the apparent resistivity data.

The tipper magnitude, phase, and dip direction, and the apparent resistivity profiles at 100 Hz are shown in Figure 5. The phase of the peak tipper is only 1 degree, indicating the effect of the overburden layer is negligible. Assuming that the contact extends to the surface and using the values of 22 degrees for ϕ_r and 0.4 for F_x in the chart given in Figure 3, the contact resistivity contrast is 400:1 with a dip of less than 20 degrees to the northeast. The conductive half-width of 150 m corresponds to 1.4 skin depths in Figure 4. From equation (1) the resistivity of the conductor is 4.5 Ω·m and the resistivity of the resistor is 1 800 Ω·m.

Although the anomaly is from a bed rather than a simple contact, the graphic interpretation method yields satisfactory results for the dip and formation resistivities. The very small response contributed from the northeastern contact can be ignored. For steeper dips the response would increase, giving the recognizable response of a conductive bed. As the dip increases the interpretation as a contact would prove to be less and less suitable and a dike model should be used.

Discussion

Our simple method for interpreting the tipper response of subsurface structure allows the analysis of data profiles over the common geologic features of a dipping contact, and a covered

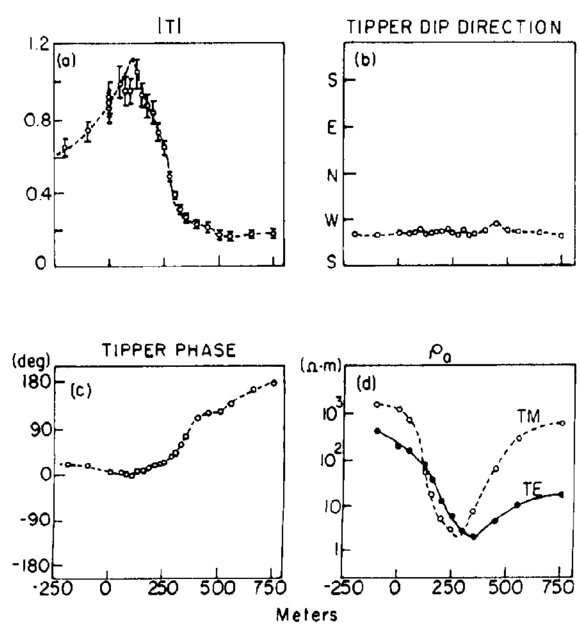

FIG. 5. Dipping contact example: North-central Washington profiles at 100 Hz, tipper magnitude, tipper dip direction, tipper phase, and apparent resistivity. Bars are 50% confidence level (not shown where smaller than symbol).

vertical contact. The charts, which relate the profile response to the characteristics of the physical models, can be used in the field to interpret single frequency profiles. By using only the phase and shape of the profile, the effect of orientation of the target to a fixed transmitter is limited. This allows reasonable interpretation of data acquired using VLF radio transmitter sources. The example of the contact interpretation demonstrates that reasonable results can be obtained by this procedure. This method of interpretation is best used for the examination of reconnaissance profiles, but it can also be used to obtain a starting point for more detailed inversion using other methods.

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Combined Mode Transient Electromagnetic Survey for Mineral Exploration: A Case History MIN 2.7

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The most popular mode of transient electromagnetic (TEM) surveying used for mineral exploration in North America is a "Turam mode". In this mode a large rectangular transmitter loop occupies a fixed position and the receiver moves along the survey lines. The results of the survey are presented as electromotive force (emf) profiles along the surveyed lines. A different survey mode, "combined mode", was tested for uranium exploration in northern Saskatchewan, Canada. In this mode a square transmitter loop occupied successively adjacent positions along the survey line. The measurements of three mutually orthogonal components of time derivative of secondary magnetic field were taken using a Geonics EM-37 transient system in the center of the transmitter loop. Data obtained were processed and interpreted as emf profiles and as transient sounding curves. The results of both interpretations show the same structure. The survey mode used was found to be very effective for geoelectrically complex regions. Additional geophysical and geologic information can increase the accuracy and reliability of the interpretation.

The TEM method has been used for many years in mineral exploration. In North America the method is usually employed in "Turam mode". In this mode a large rectangular transmitter loop occupies a fixed position. Measurements are then taken inside and/or outside of the transmitter loop using a receiver moving along preset survey lines. This survey mode provides high productivity and is very effective for relatively simple geoelectric conditions. However, in the case of complicated geoelectric structure (such as presence of multiple conductors, variable thickness of conductive overburden, etc.) the Turam mode data can be easily misinterpreted (Spies and Parker, 1984).

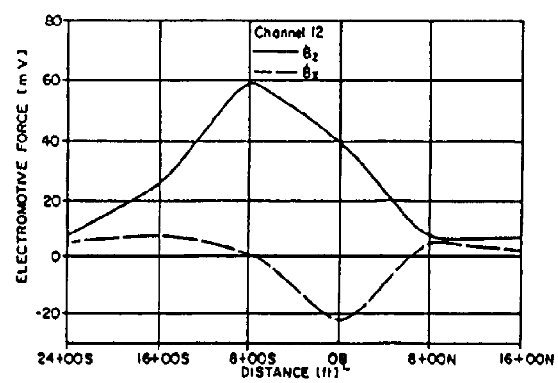
The Athabasca basin in northern Saskatchewan, Canada, is characterized by complex geologic and geoelectric conditions. Basically, the subsurface consists of a thick sandstone unit overlying crystalline basement. The resistivity and thickness of the sandstone unit are highly variable. In this environment uranium deposits are usually associated with graphitic schists. Conductive zones within the basement due to graphitic mineralization were

FIG. 1. Transmitter-receiver configuration.

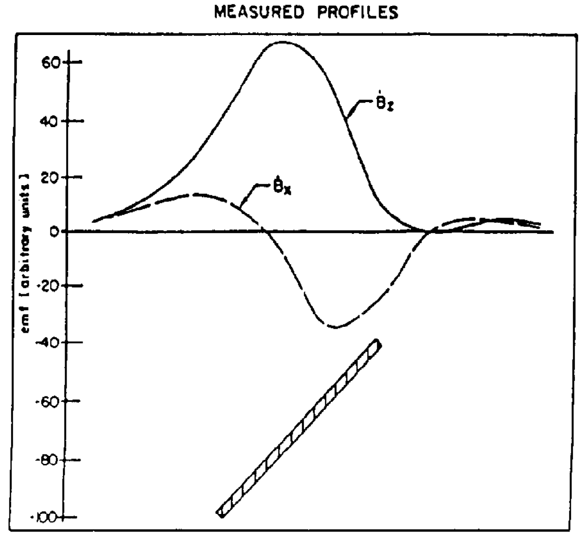
veying proved to be ineffective due to the complex geoelectric structure of the survey area. As a result the "combined mode", was tested. In the combined mode a square transmitter loop occupies successively adjacent positions along the survey line (Figure 1), so that two neighboring loops would have a common side. The measurements of three mutually orthogonal components of time derivative of secondary magnetic field are taken in the center of each transmitter loop. The data gathered were plotted as emf profiles and compared to computer-generated profiles for plate-shaped conductors. In addition, the vertical component was processed to obtain late stage apparent resistivity curves, which were interpreted using the developed technique.

Figure 2 shows the emf profiles based on the results of measurements and computer modeling for the radial and vertical components. Comparing these profiles, a plate type conductive body dipping southward can be interpreted to occur in the subsurface south of Station 0 + 00.

Figure 3 shows the section obtained from formal interpretation of the late stage apparent resistivity curves. The curves measured at the northern and southern ends of the survey line are also shown. The technique of interpretation developed by Kaufman and Keller (1983) and Rabinovich (1973) was used. The inter-



MEASURED PROFILES



MODELLED PROFILES